# Low β resonators performance

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May 12, 2010

# Superconducting low-β cavities

Most of the existing superconducting cavities are QWR for heavy ion acceleration, the most successful (6 heavy ions accelerator using QWR are in operation). The cavity for proton machines are similar in principle, but there are differences especially important below $\beta < 0.3$ :

- Higher frequency
- Larger power coupler, rf ports and beam aperture (higher beam currents)
- Higher requirements for accelerating field quality.

To meet new requirements a number of new low-β cavity designs are developed: re-entrant, spoke, HWR, ladder, CH multigap. Unfortunately, there are numerous ongoing projects , but very low statistics, mostly from single measurements. Let's consider some projects as examples of different cavity design implementations:

- Advanced Accelerator Application – Single spoke resonator
- TRASCO – Re-entrant cavity
- XADS – Single spoke resonator (original option)
- IFMIF – Half wave resonator
- FRIB – Half wave resonator

Useful to know

- ISAC-2 – Quarter wave resonators
- SARAF – Halve wave resonator

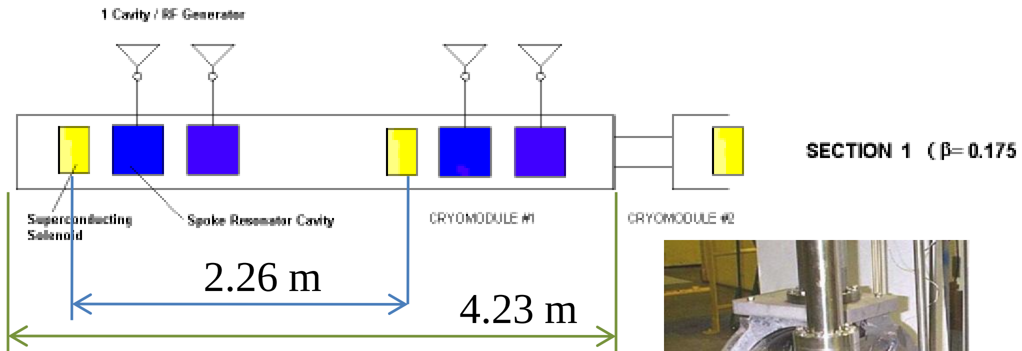
Some statistics available

# Advanced Accelerator Applications (LANL proposal PAC2001)

LEDA RFQ, 6.7 MeV, 13 mA, CW,

Table 1: Superconducting Linac Design Parameters

| | Section 1 | Section 2 | Section 3 |
|---|---|---|---|
| Structure Type | 2-gap spoke | 3-gap spoke | 3-gap spoke |
| Frequency (MHz) | 350 | 350 | 350 |
| Cavity Geometric Beta | 0.175 | 0.2 | 0.34 |
| Cavity Bore Radius (cm) | 2.0 | 3.5 | 4.0 |
| L-cavity (active) (m) | 0.10 | 0.20 | 0.33 |
| L-cavity (physical) (m) | 0.20 | 0.30 | 0.43 |
| L-magnet (m) | 0.15 | 0.15 | 0.15 |
| L-warm-space (m) | 0.30 | 0.30 | 0.30 |
| L-cryomodule (m) | 4.23 | 5.80 | 6.62 |
| L-cryoperiod (m) | 4.53 | 6.10 | 6.92 |
| L-focusing period (m) | 2.26 | 3.05 | 3.46 |
| Cav/cryomodule | 4 | 6 | 6 |
| Cav/section | 32 | 48 | 48 |
| No. of cryomodules | 8 | 8 | 8 |
| DW/cav (MeV) | 0.08 – 0.35 | 0.34 - 0.78 | 0.86 - 1.40 |
| Synchronous Phase (deg) | -45 to –32 | -32 | -32 to –28 |
| EoT (MV/m) | 1.13 - 4.16 | 2.02 - 4.68 | 3.06 - 4.76 |
| Win,section (MeV) | 6.7 | 14.17 | 43.54 |
| Wout,section (MeV) | 14.17 | 43.54 | 109.04 |
| DW/section (MeV) | 7.47 | 29.37 | 65.50 |
| Section Length (m) | 36.21 | 48.82 | 55.39 |





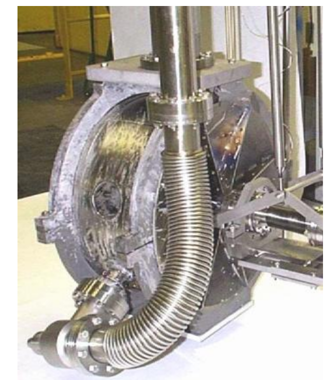


Figure 3: Cutaway of 2-Gap Spoke Resonator.

Probably the first modern design of SSR. Tested in test cryostat.

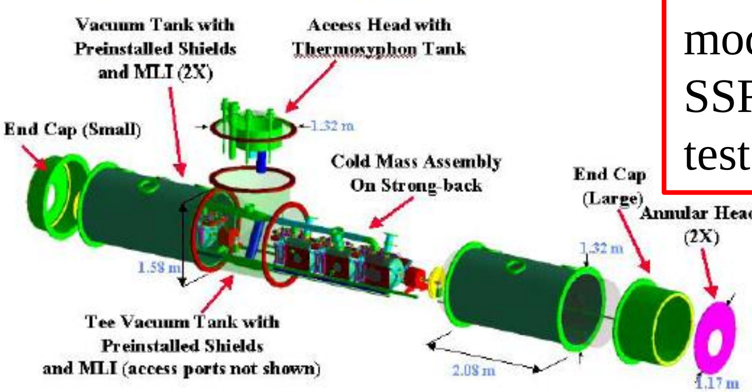



Figure 2: Conceptual Section 2/3 Cryomodule Layout.

# TRASCO (TRAsmutazione di SCOrie, INFN/ENEA)

30 mA, CW

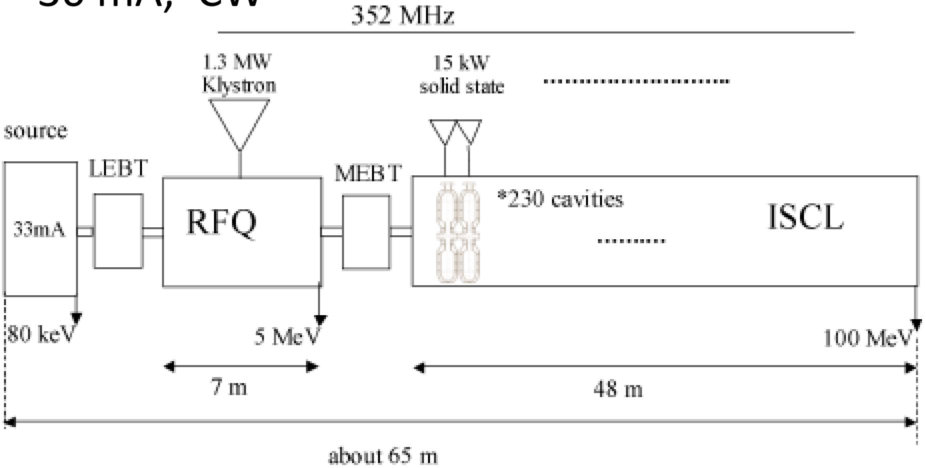



Figure 1: Block diagram of the linac.

Natural layout

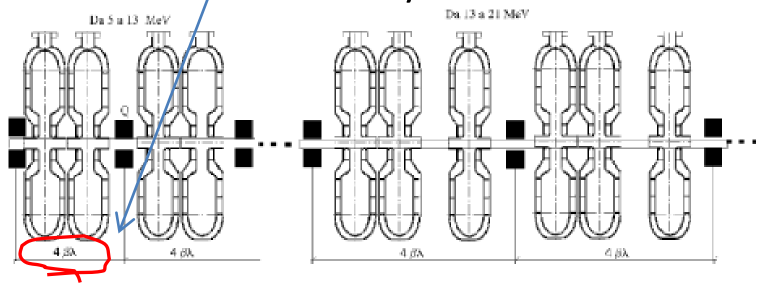


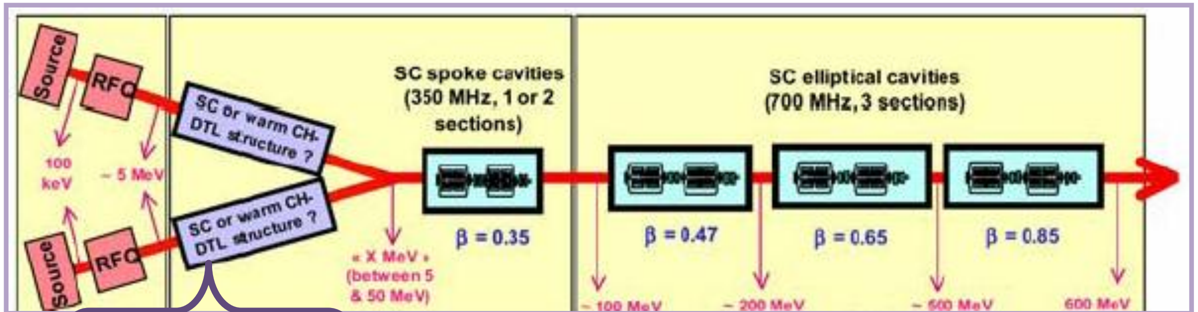
Figure 4: ISCL layout: reentrant cavities and quadrupoles in the cyrostat.

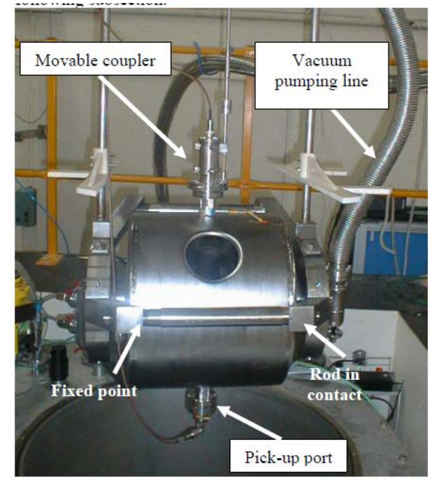
Table 1. Reentrant cavity parameters

| | | |
|---|---|---|
| Total length | $\boxed{135}$ | mm |
| effective length | 80 | mm |
| bore radius | 15 | mm |
| gap length | 30 | mm |
| frequency | 352 | MHz |
| $U/E_a^2$ | 0.034 | $J/(MV/m)^2$ |
| $E_p/E_a$ | 3.05 | |
| $H_p/E_a$ | 30.6 | Gauss/(MV/m) |
| $\Gamma=R_s\times Q$ | 83.9 | $\Omega$ |
| $\beta$ | $\geq 0.1$ | |

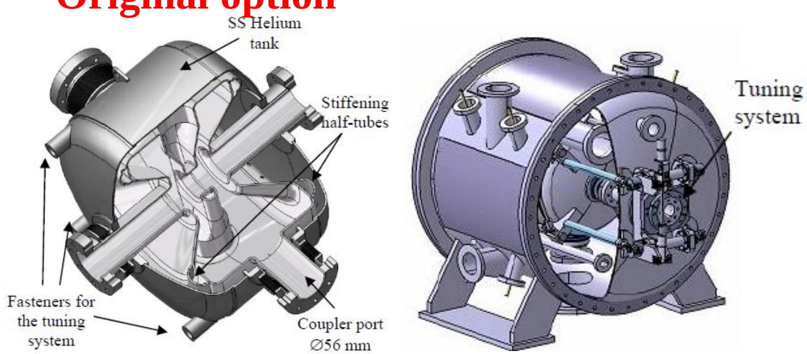
Tested in test cryostat

# XADS (eXperimental Accelerator Driven System)




Original option



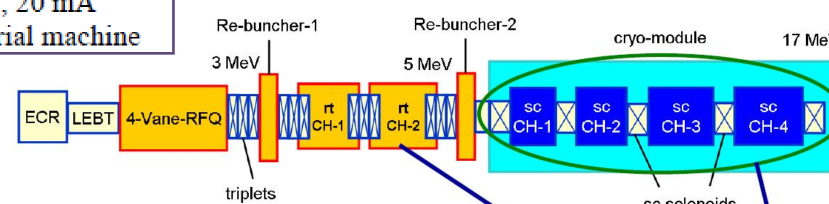

| XADS |
|---|
| 600 MeV |
| • 6 mA max. on target<br>• 10 mA rated |
| Less than 5 beam trips (>1sec) per year |
| The concept must stay valid for a 1 GeV, 20 mA industrial machine |

B03 cavity tested at 4K and 2K

Table 2: Layout of the SC linac used for the fault-tolerance simulations; focusing is ensured by warm quadrupole doublets

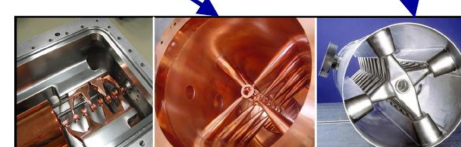
| SC linac sections | Energy range | Nb of cavities |
|---|---|---|
| Spoke 2-gap, 352.2 MHz, β=0.15 (~30 metres) | 5 - 17 MeV | 36 (2 per lattice) |
| Spoke 2-gap 352.2 MHz, β=0.35 (~50 meters) | 17 - 91 MeV | 63 (3 per lattice) |
| Elliptical 5-gap, 704.4 MHz, β=0.47 (~60 meters) | 91 - 192 MeV | 28 (2 per lattice) |
| Elliptical 5-gap, 704.4 MHz, β=0.65 (~100 meters) | 192 - 498 MeV | 51 (3 per lattice) |
| Elliptical 6-gap, 704.4 MHz, β=0.85 (~25 meters) | 498 - 615 MeV | 12 (4 per lattice) |

## Final design of 5-17 MeV section




Superconducting CH-cavities

| | |
|---|---|
| Frequency | 352 MHz |
| Effective voltage | 2.5-3.5 MV |
| Gradient | 3.9 MV/m |
| Nr. of cells: | 13-14 |
| Focusing | Sc solenoids |



# IFMIF (International Fusion Materials Irradiation Facility) EVEDA (Engineering Validation and Engineering Design)

Originally
5-40 MeV CW DTL
175 MHz,
125 mA CW

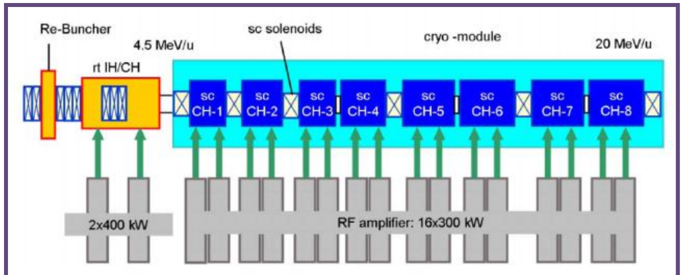



Figure 2: Layout of the H-mode-linac for IFMIF proposed by IAP. The linac consits of one rt H-mode cavity and a chain of 8 superconducting CH-cavities. Each cavity is fed by two amplifiers and two power couplers.

EPAC08 (end of June)

LINAC08 (end of Sept.)

Current design

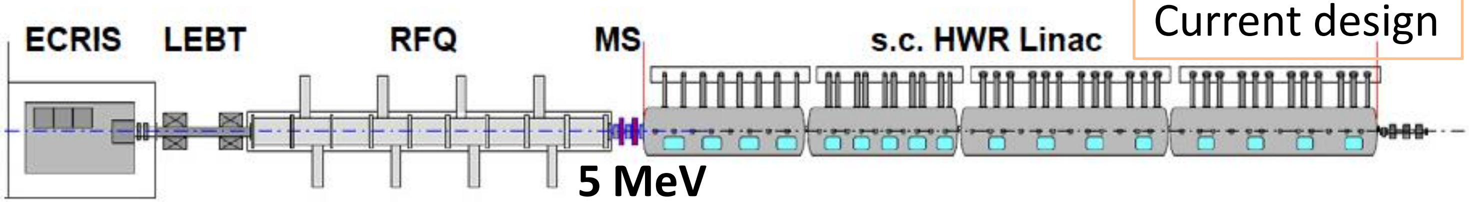
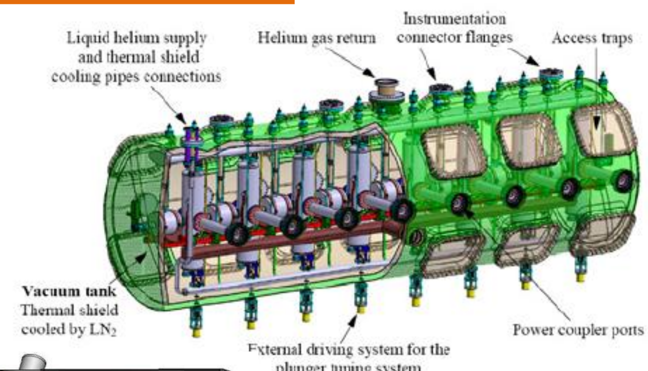
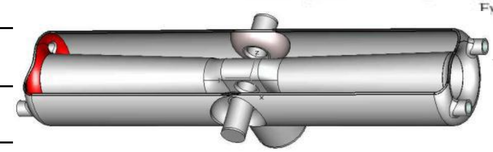



Figure 8: Layout of the superconducting Linac for IFMIF.

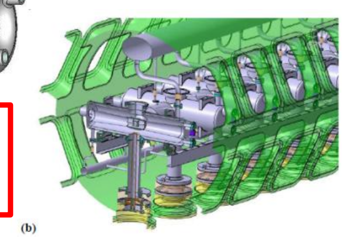
Table 1: Main Parameters of the HWR Linac

| Cryomodule | 1 | 2 | 3 & 4 |
|---|---|---|---|
| Cavity β | 0.094 | 0.094 | 0.166 |
| Cavity length (mm) | 180 | 180 | 280 |
| Beam aperture (mm) | 40 | 40 | 48 |
| Nb cavities / period | 1 | 2 | 3 |
| Nb cavities / cryostat | 1 x 8 | 2 x 5 | 3 x 4 |
| Nb solenoids | 8 | 5 | 4 |
| Cryostat length (mm) | 4.64 | 4.30 | 6.03 |
| Output energy (MeV) | 9 | 14.5 | 26 – 40 |



Multipacting simulated with my help.



# FRIB (Facility for Rare Isotope Beams, MSU)

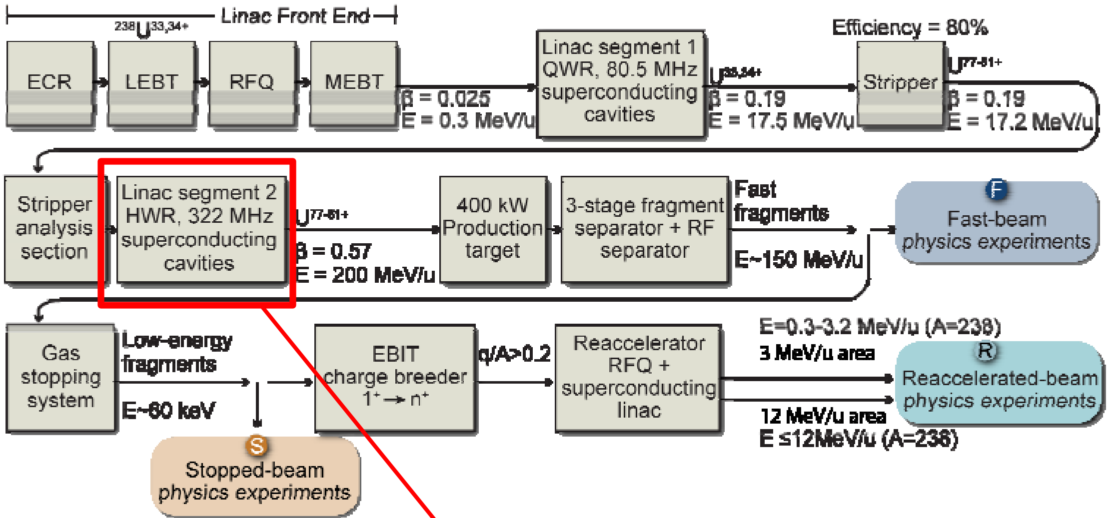
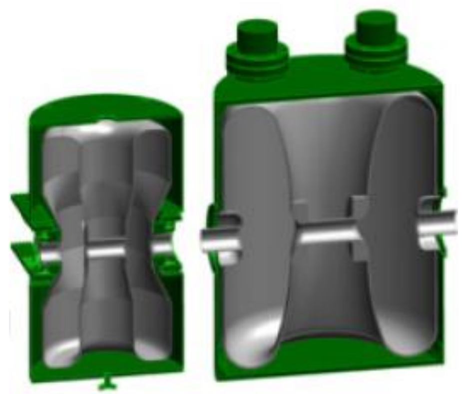



Table 2: Main parameters of SC accelerating structures and cryomodules used in Linac Segments 1 and 2

| SC linac | Segment 1 | | Segment 2 | |
|---|---|---|---|---|
| Cavity Type | QWR | QWR | HWR | HWR |
| Frequency (MHz) | 80.5 | 80.5 | 322 | 322 |
| $\beta_{opt}$ | 0.041 | 0.085 | 0.285 | 0.53 |
| Aperture (mm) | 30 | 30 | 30 | 40 |
| $E_p$ (MV/m) | 30 | 30 | 30 | 32 |
| $B_p$ (mT) | 53 | 67 | 82 | 77 |
| $N_{cavity}$ per module | 8 | 8 | 6 | 8 |
| $N_{cryo}$ | 2 | 12 | 12 | 19 |
| Operating Temp. (K) | 4.5 | 4.5 | 2 | 2 |
| Solenoid field (T) | 9 | 9 | 9 | 9 |
| $N_{solenoid}$ per module | 7 | 3 | 1 | 1 |



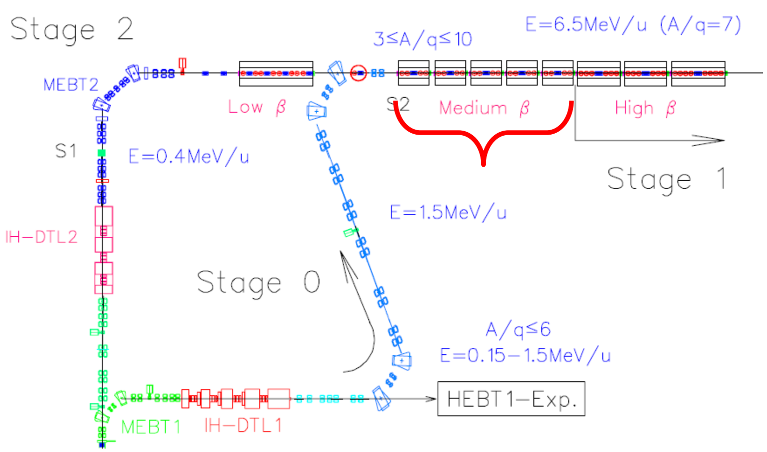
$\beta_{opt}$=0.285 322 MHz

$\beta_{opt}$=0.53 322 MHz

$\beta_{opt}$=0.041 80.5 MHz

$\beta_{opt}$=0.085 80.5 MHz

# TRIUMF ISAC-2



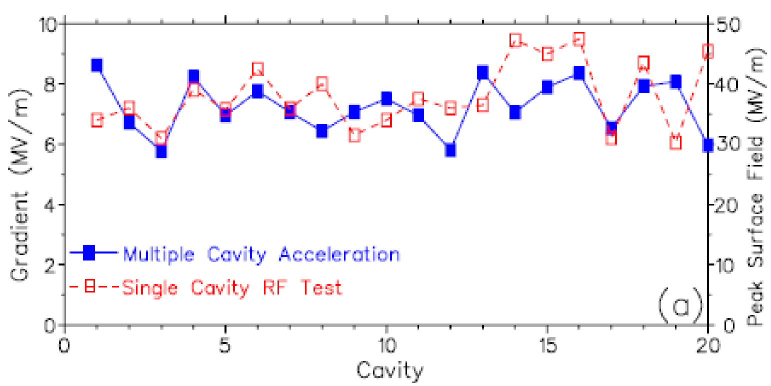
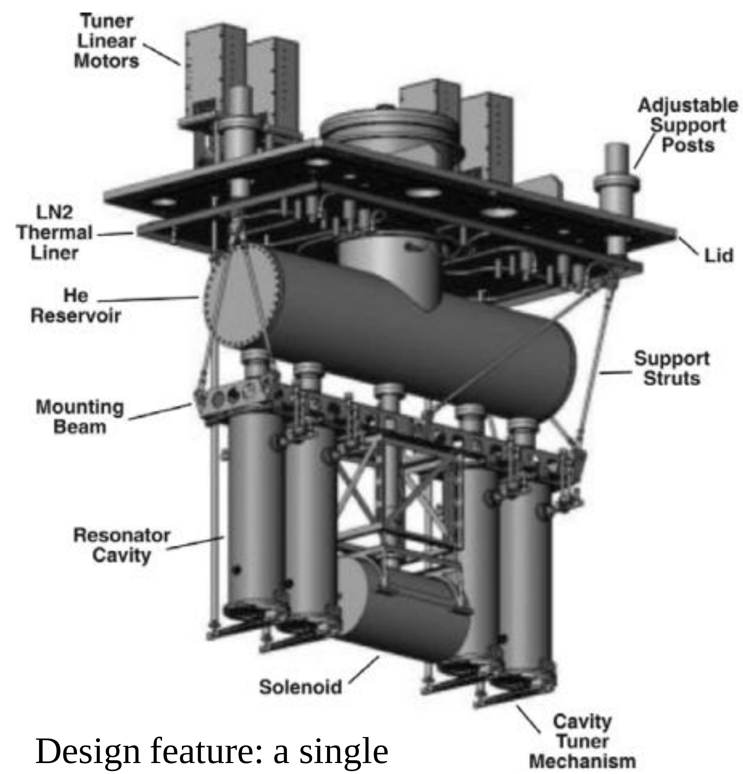




Figure 4: Average cavity gradients for the three $A/q$ values and for 7 W cavity power. Results are inferred from the step energy gain per cavity during acceleration. Also shown are gradients from initial single cavity characterizations.

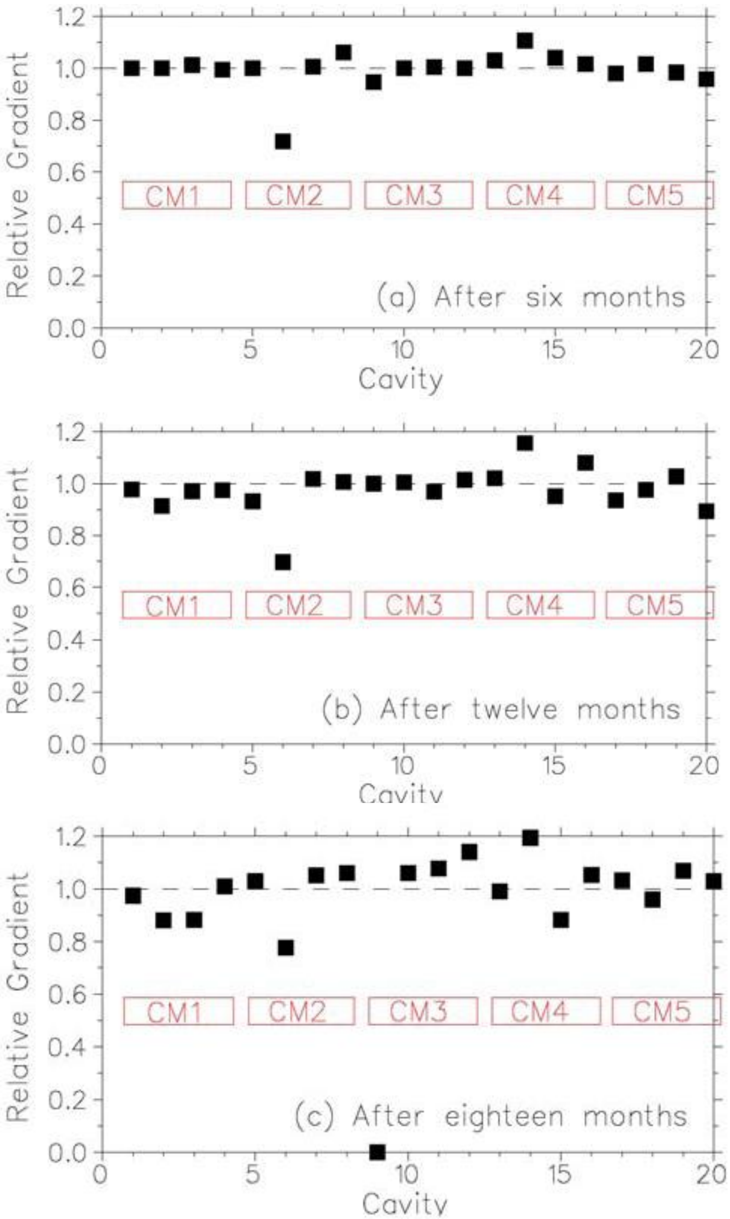
Only 5% down

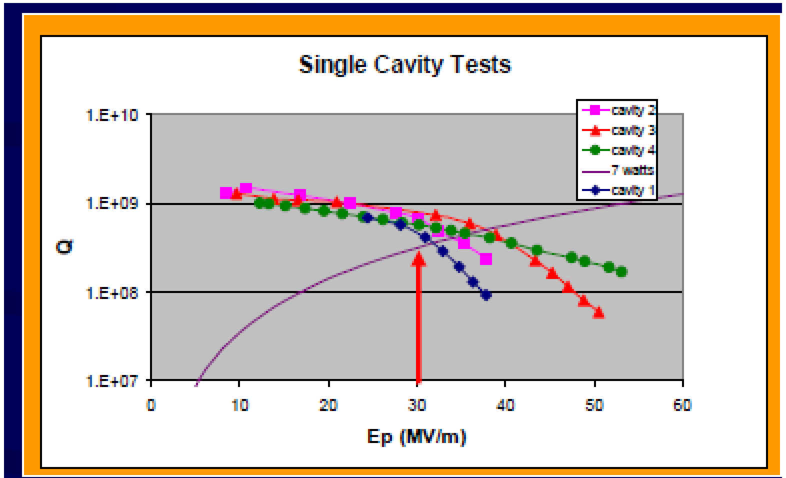
F= 106.MHz. The first eight QWR have a design velocity of 0.057 while the remaining twelve have a design velocity 0.071.

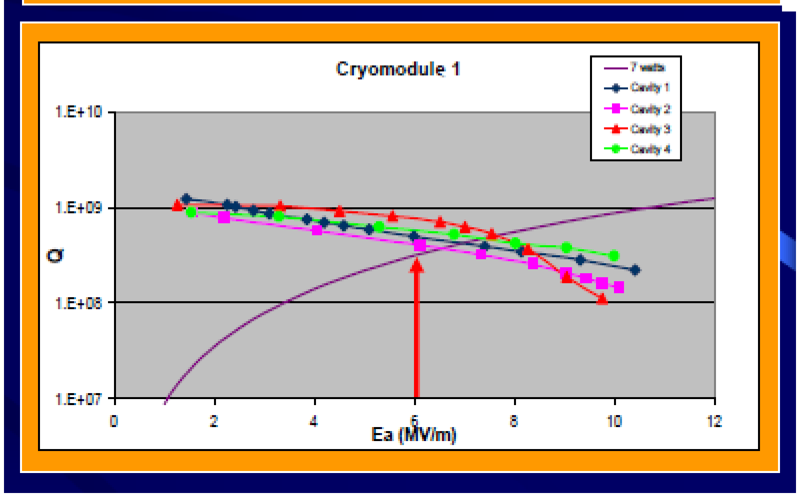



Design feature: a single vacuum space for thermal isolation and beam/rf volumes.

# ISAC-2. Gradients over time.




“During the run we experience an **instability** problem with **cavity number nine**. This cavity was turned off and the downstream ones retuned to a higher gradient. The average gradient of these cavities went from 6.5 MV/m to 7 MV/m. The overall average remained the same. “

# ISAC-2. Some conclusion

During the beam delivery period the SC-linac ran well with an integrated downtime of only 32 hours out of 1100 (**3%**) split roughly 50/50 between the cryogenic system and the cavities. The cavity downtime was due to aging of the tubes in five of the rf amplifiers. Records showed that the amplifier tubes had more than 9000 operating hours. The tubes have since been replaced in all the twenty amplifiers.

The problem with cavity #9 is unclear at the moment. The cavity #6 doesn't look good as it was before beam test.

TRIUMF: "The performance represents the highest accelerating gradient for any operating cw heavy ion linac. The experience from the year and a half of operation indicates stable cavity performance with little or no cavity degradation."

# SARAF (Soreq Applied Research Facility)

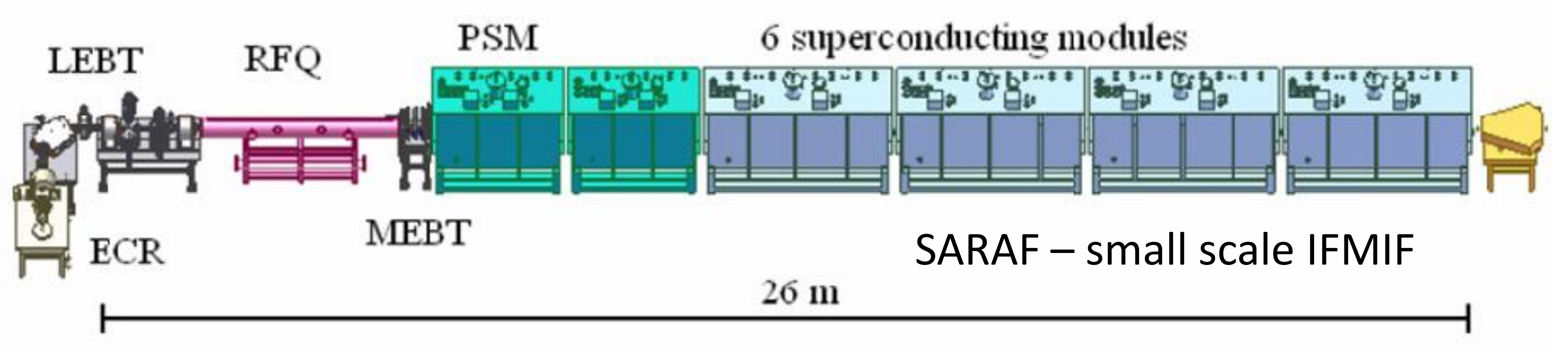
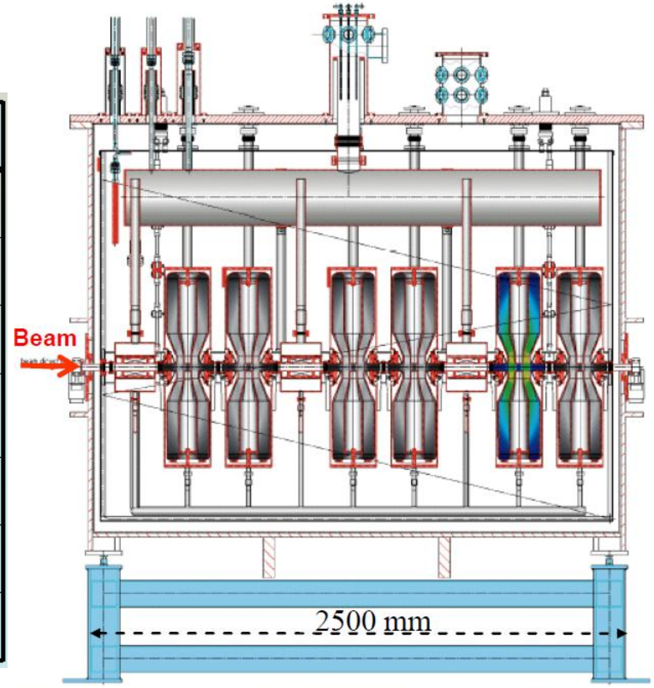



Figure 2: Schematic layout of the SARAF.

SARAF – small scale IFMIF

176 MHz Four-rod RFQ, 5 MeV

| Parameter | Value | Comment |
|---|---|---|
| Ion Species | Protons/Deuterons | M/q ≤ 2 |
| Energy Range | 5 – 40 MeV | |
| Current Range | 0.04 – 2 mA | Upgradeable to 4 mA |
| Operation mode | CW and Pulsed | PW: 0.1-1 ms; rep. rate: 0.1-1000 Hz |
| Operation | 6000 hours/year | |
| Reliability | 90% | |
| Maintenance | Hands-On | beam loss < 1 nA/m |



ACCEL

# Parameters of $\beta = 0.09$ SARAF HWR

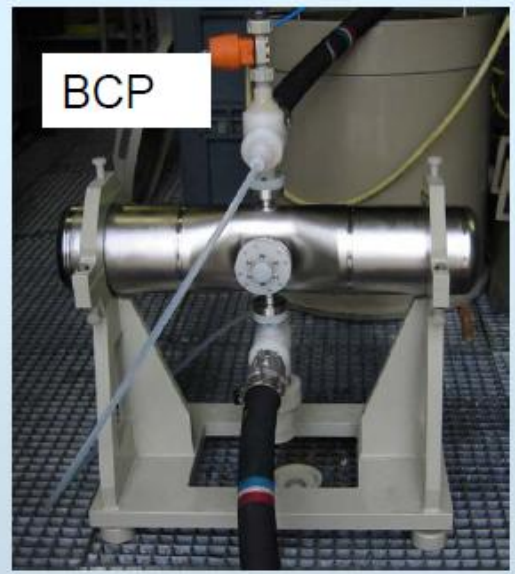
Cavities are produced out of RRR > 250 bulk niobium, design goal: $E_p$ = 25 MV/m

| Parameter | Value | Unit |
|---|---|---|
| Frequency | 176 | MHz |
| Cavity height h | 835 | mm |
| Diameter of inner conductor | 80 | mm |
| Diameter of outer conductor | 180 | mm |
| Wall thickness | 3 | mm |
| Cavity volume | 17 | l |
| Accelerating length[1] $L_{acc}$ | 99 | mm |
| Optimum beta | 9 | % |
| Geom. constant G = $R_S$ x $Q_0$ | 24.5 | W |
| Shunt Impedance R/Q | 164 | W |
| $E_{peak}$ / $E_{acc}$ | 2.9 | |
| $B_{peak}$ / $E_{peak}$ | 2.1 | mT/MV/m |
| $B_{peak}$ / $E_{acc}$ | 6.2 | mT/MV/m |

[1] Measured from start of the first to the end of the second acceleration gap of the HWR, excluding leakage field in beam tubes

- The 1st prototype is under testing
- The 1st cryomodule is under construction
- The $\beta$ = 0.15 prototype and cryomodules will follow

Done




$\beta$ = 0.09 prototype

# SARAF. Cavity conditioning

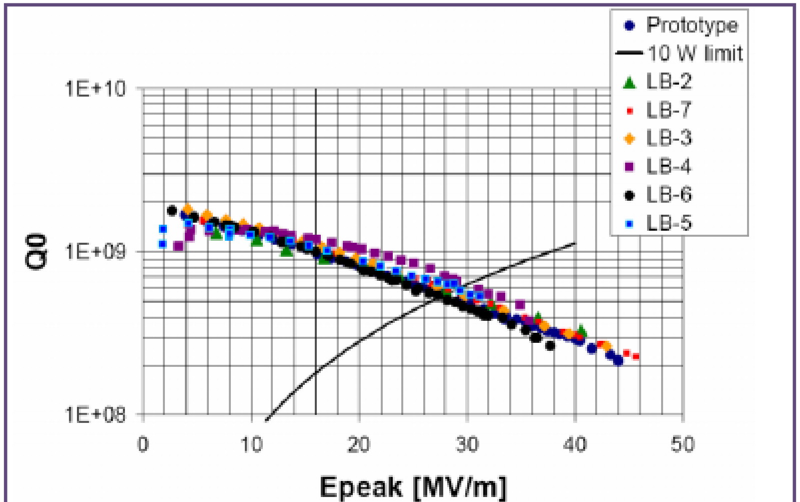



Figure 2: Test results of a the halfwave resonators produced for the SARAF linac.

Single cavity test at ACCEL, 2006.
All cavities exceeded design parameters

Multipacting at very low power level in prototype cavity. They had change a geometry

Cavity RF losses at 4.5 K. High losses disabled measurements for cavities 4 and 6 at 25MV/m.

| | At RI (single cavity) | At Soreq (inside PSM) | | | |
|---|---|---|---|---|---|
| Cavity # | Vertical Test [W] | Before Processing [W] | | After Helium Processing [W] | |
| | 25 MV/m | 20 MV/m | 25 MV/m | 20 MV/m | 25 MV/m |
| 1 | 7.3 | 1.9 | 7 | 2.2 | 5.5 |
| 2 | 7.3 | 3.0 | 6.3 | 4.8 | 8.7 |
| 3 | 6.3 | 12.3 | 16.8 | 7.0 | 14.8 |
| 4 | 6.3 | 11.1 | --- | 3.9 | 10.6 |
| 5 | 5.5 | 5.4 | 15.1 | 3.3 | 8.8 |
| 6 | 7.3 | 9.6 | --- | 5.4 | 10.7 |
| Total | 40 | 43.3 | --- | 26.6 | 59.1 |
| Target | 72 | | 72 | | 72 |

At that point it was decided to try Helium processing for cavities 3, 4 and 6. The cavities were filled with high purity helium gas (99.9999%), to a pressure of 4  10-5 mBar. The PLL was used to apply high power pulses (43 MV/m in peak field) with 5 Hz repetition and about 20 msec length. Each cavity was processed for several hours, until no more  processing events were observed and the radiation level was stable.

# SARAF proton operation. Beam transmission

| | |
|---|---|
| $E_p$ [MeV] | 3.7 |
| Beam Duty Cycle [%] | 0.01 |
| $I_p$ @ LEBT [mA] | 5.0 |
| $I_p$ @ D-Plate [mA] | 2.1 |
| RFQ RF Duty Cycle [%] | 100 |
| PSM RF Duty Cycle [%] | 100 |

4 MeV nominal

Transmission = 42%

Subsequent runs with lower LEBT current yielded higher transmission, up to 70%

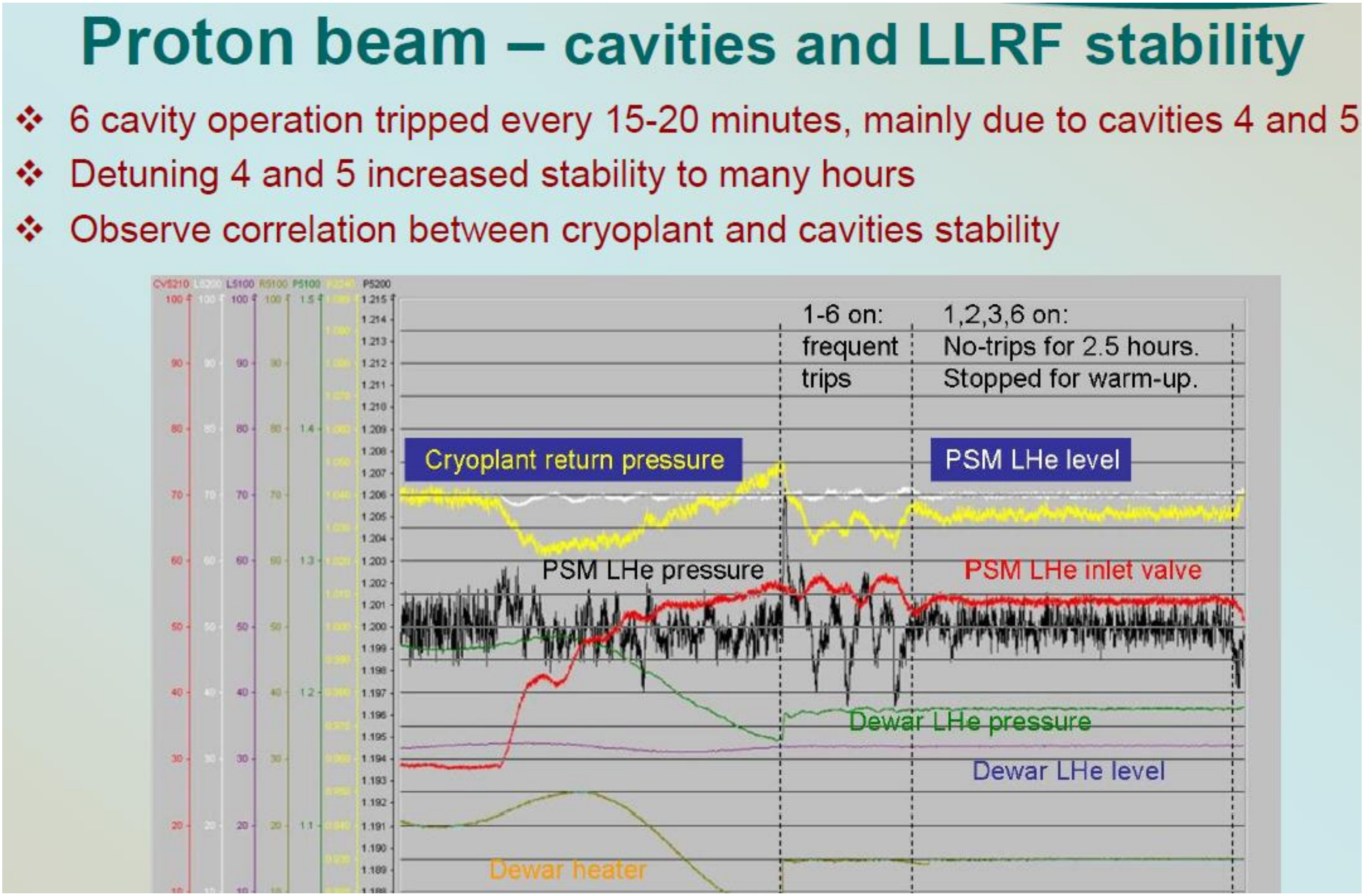
RFQ transmission

| | |
|---|---|
| Transmission [%] (@ 0.5 mA) | 80 (90) |
| (@ 2.0 mA) | 70 (90) |
| (@ 4.0 mA) | 65 (90) |

Big problems with RFQ. It melted several times. But SARAF is optimistic about it.

Overall low transmission is still not well understood.

## Cavity perfomance during operation




August 11, 2009
6:27 – 13.13

# SARAF. Summary and outlook

• 2.1 mA proton beam has been accelerated through the RFQ and PSM up to 3.7 MeV

• RFQ transmission is low

- Probable causes: high LEBT emittance, LEBT-RFQ misalignment, non-uniform RFQ field (?)

• Longitudinal emittance is high

- Probable cause: choice of non-linear conditions, non-uniform RFQ field(?)

• Transversal emittance is low

- Probable cause: Losses cut off part of the beam's phase space 0

• Unstable cavity 4 and 5

- Possible cause: insufficient processing of cavities 4 and 5. Operation at medium acceleration voltage of these cavities might cause significant changes in the power load of the cryoplant, which in turn cause liquid Helium pressure variations that trip the cavities.

• High losses in cavities 3,4 and 6 after installation in cryostat. Poor handling?